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IDENTIFICATION OF FUTURE ENGINEERING-DEVELOPMENT NEEDS OF ALTERNATIVE CONCEPTS FOR MAGNETIC-FUSION ENERGY*

by

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ABSTRACT

A qualitative identification of future engineering needs of alternative fusion concepts (AFCs) is presented. These needs are assessed relative to the similar needs of the tokamak in order to emphasize differences in required technology with respect to the well documented mainline approach. Although nearly thirty AFCs can be identified as being associated with some level of reactor projection, redirection, refocusing, and general similarities can be used to generate a reduced AFC list that includes only the bumpy tori, stellarators, reversed-field pinches, and compact toroids. Furthermore, each AFC has the potential of operating as a "conventional" (low power density, superconducting magnets) or a "compact", high-power-density (HPD) system. Hence, in order to make tractable an otherwise difficult task, the future engineering needs for the AFCs are addressed here for conventional <u>versus</u> compact approaches, with the latter being treated as a generic class and the former being composed of bumpy tori, stellarators, reversed-field pinches, and compact toroids.

I. INTRODUCTION

The development and eventual commercialization of magnetic fusion energy (MFE) is presently being pursued in the US through two mainline concepts, the tokamak and the tandem mirror, with a number of promising but less developed approaches being funded as backup or alternative fusion concepts (AFCs). In some instances an AFC may present an option rather than a backup to the mainline approaches. The reasons for pursuing AFCs are the promises for less expensive systems that may be easier to maintain and operate while requiring less development time and dollars; the need for lower technology and better, more flexible operating characteristics (steady-state plasma, use of advanced fuels,

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etc.) contributes to the reasons for pursuing certain AFCs. In a sense, the AFCs present both a backup and a competition to the mainline in the evolution of an optimal means to confine plasma for the economic production of fusion power.

Numerous, relatively low-level reactor studies of the AFCs have been reported over the past decade. This paper attempts to translate the results of these parametric systems, tradeoffs, and conceptual design studies into an overview of engineering technology requirements; such a listing of requirements, although qualitative, ultimately must be used to develop and implement an R&D program plan that optimally supplies the long-term engineering needs of MFE. Only the future engineering needs of the AFCs are addressed here. Hence, in relating the results of system studies to future engineering needs, large variations in physics uncertainty and promise, stage of development, and maturity of concept among the mainline and AFC approaches must be recognized. The degree of common technology among the various MFE approaches is particularly important in fostering potentially promising AFCs on the basis of more rapidly developing physics, nuclear, and materials data bases that are emerging to support the mainline approaches.

The engineering development needs for the mainline tokamak have been quantified by detailed conceptual studies of both first-generation tokamak engineering experiments[1,2] and commercial power reactors.[3] To a lesser extent, but nevertheless at a significant level of effort and conceptual design detail, are studies of the Tandem Mirror Reactor (TMR),[4-6] as well as nearer-term engineering devices[7,8] based on the tandem mirror confinement principle. Complementing both the tokamak and tandem-mirror mainline approaches are the AFCs. The status of reactor designs for tokamaks, tandem mirrors, and AFCs have been summarized quantitatively in a recent review paper,[9] and an even more recent status has been reported by an IAEA workshop.[10]

Table I gives an updated version of a previous[9] AFC summary. Many of the reactor designs suggested for these twenty-eight AFCs are based on study efforts that, relative to the tokamak, were limited both by the available manpower and the physics data base. Approximately 11-12 of the AFCs listed on Table I are being examined experimentally, while an awareness of reactor technology needs and related engineering constraints is simultaneously being maintained. Furthermore, many of the AFCs receiving attention share both a common physics basis and projected technology R&D needs with both the mainline and other AFCs. Both the programmatic narrowing of the AFC spectrum displayed on Table I as well

TABLE I

SUMMARY OF ALTERNATIVE CONCEPTS FOR MAGNETIC FUSION

	Reference[a]
I. Toroidal	
A. Steady state	
Stellarator	11-15
Torsatron	16,17
Bumpy torus (EBT/NBT)[b]	18-24
Toroidal bicusp (Tormac)	[25-27]
Surface magnetic confinement (Surmac)	28,29
B. Long pulsed	
Reversed-field pinch (RFPR)	30,31
Compact Reversed-field pinch (CRFPR)	32,33
Ohmically-heated torus (OHTE)[c]	34,35
Ohmically-heated tokamak (Riggatron)	9,36-38
High-field tokamak	39,40
C. Pulsed	
Theta-pinch (RTPR)	[41]
High-beta stellarator (HBS)	[42]
Belt-shaped screw pinch (BSPR)	43,44
II. Compact toroid (CT)	
A. Stationary	
Spheromak	45,46
Field-reversed mirror (FRM)	[47-49]
Triggered-reconnected adiabatically compressed torus (TRACT)	50,51
Electron-layer field-reversed mirror (Astron)	[52]
Slowly imploding liner (LINUS)	[53-56]
B. Translating	
Spheromak	57-59
Field-reversed theta pinch (CTOR)	60-62
Moving-ring field-reversed mirror (MRFRM)	63-65
Ion-ring compressor	[66]
III. Linear	
A. Steady state	
Multiple-mirror solenoid	[67,68]
B. Pulsed	
Linear theta pinch (LTPR)	[69]
Laser-heated solenoid (LHS)	[70]
Electron-beam heated solenoid (EBHS)	[71]
IV. Very dense (fast-pulsed, linear) systems	
Fast-imploding liner (FLR)	[72]
Dense plasma focus (DPF)	[73]
Wall-confined shock-heated reactor (SHR)	[74]
Dense Z-pinch (DZPR)	75,76

(a) The [] brackets indicate concepts for which neither experimental nor systems studies activities presently exist.

(b) ELMO Bumpy Torus/Nagoya Bumpy Torus.

(c) Ohmically-Heated Toroidal Experiment.

as the pi. ical and technological commonality between certain of the surviving AFCs is u d here to make manageable an otherwise intractable task of relating reactor projections to future engineering development needs for the AFCs.

The results of the narrowing process being applied to the AFCs, in fact, is reflected by the deliberations of a recent IAEA workshop,[10] wherein the AFCs being investigated in the 1980s were grouped as follows.

- ELMO or Nagoya Bumpy torus (EBT/NBT)
- Stellarator/Torsatron/Heliotron (S/T/H)
- High-Field Torus (CRFPR, high-field tokamaks, OHTE)
- Compact Toroids [CTs, Field-reversed Configurations (FRCs) and spheromaks].

It is noted that for the purposes of this paper, as well as past reviews[9] and workshops,[10] the high-field tokamak is considered an AFC.

A further condensation of the AFCs is made for the purposes of this assessment, wherein a category termed "compact" or high-power-density (HPD) systems is identified into which is placed the CRFPR, OHTE, high-field tokamaks, and certain subelements of the CT class. The rationale for and characteristics of the HPD systems are described in Ref. 33. General concern over the dominance in mass and cost of the fusion power core [i.e., first-wall/blanket/shield/coils (FW/B/S/C)] that characterizes many of the conventional MFE approaches has led to recent serious consideration of the HPD or compact option. Fusion-power-core or system power densities that are comparable to alternative energy sources, projected costs that are relatively insensitive to large changes in the unit cost ($/kg) of the fusion power core, considerably reduced size/mass of the fusion power core with potential for block installation and maintenance, and the potential for rapid, minimum-cost development/deployment are general characteristics being sought for the compact option. The unique engineering/technology needs for the HPD systems are assessed here as a separate, generic class.

It is emphasized that, like the term "conventional", use of "compact" or "HPD" does not necessarily refer to or limit a specific confinement scheme; just as the RFP has a viable conventoral reactor embodiment,[30,31] it is possible to envisage HPD reactor versions for the tokamak[36-38] and the S/T/H.[77] This division between conventional <u>versus</u> compact systems and the communication between this grouping are shown in Table II. If a given AFC is to impact significantly the overall development of MFE, it must lead to a substantially better, more competitive reactor. Furthermore, this better reactor must be achieved on a shorter time schedule and with significantly smaller expenditure of funds than for the mainline approaches. Given steady progress in physics research for certain AFCs, these goals can be met most probably along the HPD, compact route. If the reactor embodiment for a given AFC falls into the conventional side of the division shown on Table II, it probably cannot compete with the more advanced and mature mainline approach, unless a more favorable physics data base could be developed in a relatively short time. In order for an AFC to have impact as a true option rather than merely as a backup, it must pose a true alternative; for economic reasons to be discussed that alternative may have to be compact. Ultimately, the choice between conventional and HPD options will be made on the basis of economics; in a sense, this division between conventional versus HPD must be recognized as being dictated somewhat by the history of MFE reactor evolution.

TABLE II

RELATIONSHIP BETWEEN CONVENTIONAL AND HIGH-POWER-DENSITY APPROACHES TO MAGNETIC FUSION ENERGY

CONVENTIONAL MFE		HPD MFE[a]
Tokamak	→	Riggatron AFTR(?)
TMR		
EBT/NBT		
S/T/H	→	Heliac(?)
	→	OHTE
RFPR	→	CRFPR
CT	→	LINUS TRACT (?)

[a]The symbol (?) indicates those AFC reactor concepts for which operation in the HPD mode remains to be shown through conceptual design study to be physically, technically, and/or economically feasible. HPD reactor designs have been proposed only for the Riggatron,[9,36-38] OHTE,[34,35] and CRFPR.[32,33]

II. DESCRIPTION OF AFCs

A. Background

Over the past decade and to varying levels of detail and design maturity, conceptual design studies of a wide range of magnetic fusion reactors have been reported.[9] A major goal of these studies is the assessment of technology needs for eventual implementation into an engineering R&D plan. The degree to which a given fusion approach is deemed acceptable is judged on the basis of an economic assessment, using both cost-of-electricity (COE, mills/kWeh) and unit direct cost (UDC, $/kWe) as a measure of goodness while simultaneously imposing constraints on net electric power (i.e., a measure of network compatibility). Because of differences in optimism assumed in projected physics, anticipated technology development, and costing methodology, study results ranging from highly favorable[3] to cautiously pessimistic[79] can emerge, even for the same concept.

If the present state of toroidal fusion reactor projections based on an ignited or nearly-ignited DT fuel cycle could be summarized by a simple parameter list, a synopsis similar to that given on Table III might result. Where appropriate, comparable parameters for a light-water (fission) reactor (LWR)[79,80] are also included. These four concepts, the Modular Stellarator Reactor (MSR),[13-15,81] STARFIRE (tokamak),[3] ELMO Bumpy Torus Reactor (EBTR),[23,24] and Reversed-Field Pinch Reactor (RFPR),[30,31] are considered to be conventional systems in the sense previously described; all have been proposed as optimal systems while sharing the common feature of low system power density (MWt/m^3) and high mass utilization (tonne/MWt, re: footnotes (a) and (b) on Table III) relative to the fission option. Each of the conventional fusion systems given on Table III is based on the use of superconducting coils.

A number of recent publications[78,82,83] have questioned the economic competitiveness of these conventional MFE approaches. A general call is made for higher power density (HPD) systems or systems that can generate more power for less engineering mass devoted to the fusion power core. Increases in the system power density, or decreases in the mass utilization of the fusion power core, may be required in order to assure that the fusion power core remains a small fraction of the total power plant in terms of mass and cost. For the purposes of this paper, systems that operate with system power densities or

TABLE III

SUMMARY OF KEY PARAMETERS FOR A RANGE OF
TOROIDAL CONVENTIONAL DT-FUSION REACTOR CONCEPTS

DESIGN DATE: PARAMETER DEVICE:	1981 MSR[13-15,81]	1980 STARFIRE[3]	1980 EBTR[23,24]	1978 RFPR[30,31]	1980 LWR[79,80]
Plasma radius (m)	2.11	2.38	1.0	1.2	
Major radius (m)	23.24	7.0	35.0	12.7	
Plasma volume (m^3)	2050	781	691	564	
Average density ($10^{20}/m^3$)	1.50	0.81	0.95	2.00	
Temperature (keV)	8.0	22	22	15-20	
Lawson parameter (10^{20} s/m^3)	3.7	3.0	1.7	2.0	
Average beta	0.04	0.067	0.17	0.30	
Plasma power density (MW/m^3)	2.35	4.50	4.13	4.50	90
Magnetic field (T)	6.0	5.8	5.0/2.25	3.0	
Neutron current (MW/m^2)	1.3	3.6	1.4	2.7	
Thermal power (MWt)	4800	4033	4028	3000	
Net power (MWe)	1530	1200	1214	750	1000
System power density (MWt/m^3)[(a)]	0.26	0.30	0.24	0.50	19.8(7.5)[(a)]
Mass utilization (tonne/MWt)[(b)]	9.0	3.9	10.9	3.6	0.2
Thermal conversion efficiency	0.35	0.35	0.35	0.30	0.33
Recirculating power fraction	0.08	0.167	0.15	0.17	
Net plant efficiency	0.32	0.30	0.30	0.25	
COE (mills/kWeh)[(e)]	94(1991)	67(1986)	72(1985)	80(1990)	40(1983)
Unit direct cost (\$/kWe)[(d)]	1547	1438	1737	1335	900[(e)]
Construction time (years)	10	6	5	10	8-10

[(a)] Ratio of total useful thermal power to the volume enclosed by and including the coils. The LWR case pertains to a pressurized-water reactor (PWR), and the volume used is that enclosed by the primary pressure vessel; the number in parentheses includes the steam-generator volume. The equivalent number for a boiling-water reactor is 4.8 MWt/m^3.

[(b)] Ratio of first-wall/blanket/shield/coil (FW/B/S/C) mass to the total useful thermal power. The equivalent number for the LWR, again chosen here to be a PWR, uses the mass of the primary pressure vessel. The equivalent number for a BWR is 0.37 tonne/MWt. It is noted that the mass utilization predicted for the fusion power core (FW/B/S/C) is comparable to that for the complete LWR power plant (10-15 tonne/MWt, excluding concrete but including rebar).

[(c)] Based on "then-current" dollars evaluated in the designated year.

[(d)] Based on total direct cost and net electrical power before application of indirect cost (~ 23%), interest during construction (IDC), and escalation during construction (EDC). All unit direct costs (UDCs) given in 1980 dollars.

[(e)] A nominal LWR unit direct cost taken from Ref. 89.

fusion-power-core mass utilizations that are at least an order of magnitude better than the conventional MFE systems listed in Table III are designated as compact or HPD systems. In economic terms, this criterion would assure that the reactor plant equipment remains below 30-35% of the total direct cost rather than the 60-80% values that characterize the mainline and conventional AFCs. Clearly, new demands on economic, physics, and technological performances emerge along with apparent promise for the HPD approaches.[32,33] It is for these reasons that, in addition to the conventional AFCs listed on Table II, the generic engineering needs of the HPD option are also addressed.

B. Compact AFC Systems

A heuristic rationale for pursuing the HPD option is given in Ref. 32 and 33. Generally, the prudent desire to reduce the importance of the fusion power core, in terms of volume, mass, and cost, relative to the rest of the reactor plant equipment and the balance of plant requires consideration of higher system power density for both the mainline[36-38] and the AFCs.[32-35] On the basis of these arguments, a number of HPD toroidal fusion approaches are being considered.[10] These devices generally can be classified as toroids using resistive coils to provide higher-density tokamak[37-40,84] or RFP[32-35] confinement. All such devices rely on significant Ohmic heating to achieve ignition, with the high-field tokamaks to varying degrees also requiring compressional and/or high-frequency wave heating. Of the HPD approaches being considered, power reactor embodiments have been suggested to varying levels of detail only for the Riggatron,[9,37] the OHTE,[34,35] and the CRFPR.[32,33] Typical toroidal reactor parameters for the CRFPR, OHTE, and Riggatron are given on Table IV. It is noted that the CRFPR and OHTE design points result from relatively recent studies, whereas the HPD tokamak (Riggatron) study is not as recent and, therefore, may be subject to re-adjustment.

The compact or HPD systems include the possibility of any confinement scheme, primary candidates presently being RFPs, compact toroids (spheromaks, FRCs), high-beta stellarators (i.e., heliacs), tokamaks and combinations thereof. The name "compact systems" is not intended to identify a new fusion line, but rather a regime of reactor operation that assures a significant increase in system power density, a corresponding decrease in fusion-power-core mass utilization, and a significant reduction in the cost ratio of reactor plant

TABLE IV

SUMMARY OF KEY PARAMETERS FOR HIGH-POWER-DENSITY TOROIDAL FUSION REACTORS

PARAMETER	CRFPR[32,33]	OHTE[(f)]	RIGGATRON[9]
Plasma radius (m)	0.71	0.67	0.34
Major radius (m)	4.3	5.91	0.85
Plasma volume (m^3)	42.7	52.3	1.9
Average density ($10^{20}/m^3$)	3.4	12.0[(g)]	20–30
Temperature (keV)	20[(a)]	5–6[(g)]	12–20
Average beta	0.20[(l)]	0.43[(l)]	0.20
Plasma power density (MW/m^3)	72.4	80.4	460.
Plasma current (MA)	18.5	12.4	3–4
Plasma current density (MA/m^2)	11.7	8.8	8.3–11.1
Magnetic field (T)	3.3[(b)]	11.2[(h)]	24.
Neutron current (MW/m^2)	19.5	19.5	68.
Thermal power[(c)] (MWt)	3350	2740[(i)]	1325
Net power (MWe)	1000	904	355
System power density[(d)] (MWt/m^3)	15	3.2	14[(k)]
Mass utilization[(e)] (tonne/MWt)	0.37	1.45[(j)]	--
Thermal conversion efficiency	0.35	0.40	0.41
Recirculating power fraction	0.15	0.35	0.33
Net plant efficiency	0.30	0.24	0.27

(a) Flat temperature profile, $J_0^2(\alpha r)$ density profile.

(b) Peak fields at toroidal field coil.

(c) Total useful thermal power.

(d) Based on volume enclosed by and including the coils and total thermal power.

(e) Based on total thermal power and total mass of FW/B/S/C.

(f) Ref. 35, electricity generator.

(g) Profiles given by $[1 - (r/r_p)^2]^\alpha$, where $\alpha = 2$ for T(r) and 0.25 for n(r).

(h) Peak fields at Ohmic-heating coil.

(i) Total fusion power is 3795 MWt.

(j) Of the 5500 tonne for FW/B/S/C, this particularly heavy (LiPb) blanket weighs 3200 tonne uses an unusual heavy OHC to minimize losses during startup.

(k) Based on volume of vacuum chamber and first-wall coil set, the blanket in Riggatron being far removed from the fusion power core.

(l) Poloidal betas evaluated at the plasma radius, which nearly equal the total beta.

equipment to total direct cost. A confinement scheme can operate in the HPD regime by increased first-wall loading, decreased blanket/shield thickness, and increased blanket energy multiplication. For those systems that allow efficient operation with resistive coils, only a thin heat-recovering tritium-breeding blanket may be required, leading to considerable reduction in size and increases in power density. Certain key technologies projected for HPD operation are expected to be qualitatively different than are projected for the conventional approaches. The unique D&T needs for the HPD approaches are addressed generically on the basis of the projections emerging from the preliminary studies summarized in Table IV.

C. Conventional AFC Systems

As indicated on Table II, conventional AFC reactors considered here include EBT/NBT, S/T/H, RFPR, and CTs. The EBT/NBT and S/T/H are inherently steady-state devices, whereas, like the mainline tokamak, a mechanism to drive a steady-state toroidal current is needed to achieve steady-state RFPs or CTs. Long-pulsed operation for the RFP and a number of CT reactor embodiments, however, is projected to lead to attractive reactor systems. The EBT/NBT and RFP concepts generally describe well-defined entities, whereas both S/T/H[81] and CT[85] each describe an ensemble of confinement schemes. Table III lists typical reactor parameters for the EBTR, MSR, and RFPR. The MSR design point summarized in Table III corresponds to one member of the S/T/H reactor family, a wider spectrum of S/T/H reactor design points being given on Table V. Typical CT reactor parameters for the FRCs, as opposed to spheromaks, are given in Table VI; both LINUS[53-56] and TRACT[50,51] concepts heat and burn *in situ* a stationary FRC plasmoid, whereas CTOR forms and heats the plasmoid external to the reactor with the subsequent burn occurring as the FRC plasmoid translates through a linear burn chamber. Because of the early experimental development of the CTs, as well as the preliminary nature of the reactor studies listed on Table VI, the technology R&D needs for the CT class cannot be fully assessed. It is noted that based on system power density, only the LINUS promises operation in the HPD mode, although both CTOR and TRACT systems nevertheless show significant improvement with respect to system power density and over all size relative to the conventional systems summarized in Table III.

TABLE V

SUMMARY OF STELLARATOR/TORSATRON/HELIOTRON (S/T/H) FUSION REACTOR CONCEPTS[a]

	T-1[16] $\ell=3$ $m=16$ $N=20$	HELIOTRON-H[10] $\ell=2$ $m=15$	UWTOR-M[17] $\ell=3$ $m=6$ $N=18$	MSR[13,14] $\ell=2$ $m=6$ $N=18$
Plasma radius (m)	2.3	1.8	1.72	2.11
Major radius (m)	29.2	21.0	24.1	23.24
Plasma volume (m^3)	3049	1343	1830	2050
Average density ($10^{20}/m^3$)	1.33	1.2	1.56	1.5
Average temperature (keV)	7.3	13	~10	8.0
Lawson parameter (10^{20} s/m^3)	3.0	--	1.7	3.7
Average beta	0.035	0.08	0.05	0.04
Plasma power density (MWt/m^3)	1.4	--	3.91	2.34
Magnetic field (T)	5.0	4.0	5.5	6.0
Neutron current (MW/m^2)	1.1	1.3	1.8	1.3
Thermal power (MWt)	4340	3600	5500	4800
Net power (MWe)	1400	1260	1760	1530
System power density (MWt/m^3)	0.35	0.43	0.35	0.26
Recirculating power fraction	0.08	0.05	0.08	0.08
Net plant efficiency ($\eta_{TH} = 0.35$)	0.32	0.33	0.32	0.32

[a]The design points given for Heliotron-H, UWTOR-M, and MSR should be considered interim with respect to the Ref. 10 date; reactor studies on all three S/T/H have continued since that October, 1981, workshop, and at the time of this writing work remains in progress.

The validity of any needs projection for the AFCs depends on the accuracy, depth, and realism of the previously summarized studies. Many of these concepts are evolving as new experimental data and design insight/understanding are developed. It becomes important, therefore, to recognize the status of each of the reactor embodiments. Detailed reactor designs of the HPD option do not exist, although an indepth parametric study of the compact RFP reactor (CRFPR) has been completed,[32,33,87] upon which a detailed reactor design is proceeding. A detailed design has been reported for the EBTR,[23,24] although over the passed year the EBT reactor has been under study by the Oak Ridge National Laboratory.

TABLE VI

TYPICAL PARAMETERS FOR THREE CT REACTOR CONCEPTS BASED ON THE USE OF FRCs

	LINUS[53-56](a)	CTOR[60,61]	TRACT[51,86]
Minor radius (m)	0.08/0.037(b)	0.31	0.14
Major radius (m)	0.19/0.11(b)	0.52	0.36
Separatrix radius (m)	0.28/0.15(b)	0.85-1.05	0.39-0.55
Length (m)	3.1/10.0	5.0-8.0	2.3-3.0
Plasma volume (m^3)	0.35/0.50(b)	11.4-27.7	1.1-2.9
Density ($10^{20}/m^3$)	2400/1900(b)	25-5	39-45
Temperature (keV)	15/20(b)	12-14	6-35
Averaged beta	0.55/0.60	0.87	0.85-0.69
Plasma power density(b) (MW/m^3)	5100/6700(b)	93-38	400-154
Magnetic field (T)	54/60(b)	4.2-2.0	4.7-4.3
Burn time (s)	0.0004/0.0010	2.0	0.9
Off time (s)	1.0/0.5	5.8	0.2
Neutron current (MW/m^2)	305/259	2.0	7.5
Heat flux (MW/m^2)	4.7/7.0	0.05(d)	0.23
Thermal power (MWt)	1790/3350	1050	440
Net electric power (MWe)	507/910	310	100
System power density (MWt/m^3)	4.1(c)/4.1	0.70	1.14
Recirculation power fraction	0.15/0.22	0.15	0.12
Net plant efficiency (η_{TH})	0.28/0.27	0.30	0.22
	(0.33/0.35)	(0.35)	(0.25)

(a)The NRL/Los Alamos parameters.

(b)At peak compression, where ranges are given values correspond to limits taken over the full power cycle.

(c)Calculated using reactor volume including the gas reservoir used to drive the liner. If the smaller volume enclosed by the unimploded liner is used as the basis, this parameter would be increased by a factor of ~ 5.

(d)Low values because of natural divertor action to ends of device.

As indicated in Table V, detailed machine designs are evolving for the modular stellarator,[14,15,17] the Table V data representing iterim values. Lastly, little work on the CT reactors[45-66] has been reported, the most recently completed study being given for TRACT.[51]

III. ENGINEERING AND TECHNOLOGY R&D NEEDS FOR AFCs.

The future engineering needs for both the conventional and HPD AFCs are evaluated qualitatively on the basis of generic reactor subsystems. This subsystem breakdown is given on Table VII, which also gives a qualitative ranking of technology needs for the conventional AFC reactor embodiments listed on Table II relative to the tokamak mainline. This subsystem format is also applied separately to a generic assessment of the HPD AFC approaches.

Three points should be noted in applying the systems format given in Table VII to assessing future engineering needs. First, balance-of-plant (BOP) issues are not taken into account, these BOP issues interfacing with those in Table VII primarily through the primary/secondary coolant loop systems and through the recirculating power requirements. Secondly, a strong interrelationship exists among the subsystems given in Table VII (e.g., impurity control impacts strongly plasma engineering, nuclear, and magnetic subsystems). A recent study and workshop,[88] in fact, has quantitatively addressed the engineering facility needs for both the mainline and a majority of the AFC approaches. Thirdly, the extensive and multifaceted materials R&D needs associated with each subelement of Table VII are not explicitly discussed in this paper. This section gives a qualitative rationale for the ranking suggested in Table VII for the conventional AFCs, as well as for the HPD options. The following Sec. IV. gives a tabular summary of the remarks made herein.

A. Technology R&D Needs for Conventional AFCs

The conventional AFC reactor embodiments being considered here are EBT/NBT, S/T/H, RFP, and CT. With the possible exception of the CTs, the engineering needs for each of the subsystems listed in Table VII appear to be similar to or are somewhat more demanding than the tokamak. The ranking given on Table VII is based on the following qualitative inferences of future engineering needs, as measured relative to the better quantified needs of the mainline approaches.

1. Plasma Engineering System Taken as a composite, the technology required of the plasma engineering system appears to be more difficult, comparable, somewhat easier, and easier relative to the tokamak, respectively,

TABLE VII

SUMMARY OF KEY MFE REACTOR SYSTEMS USED TO ASSESS TECHNOLOGY R&D NEEDS WITH TOKAMAK-BASED RANKING BEING APPLIED TO THE CONVENTIONAL AFC SYSTEMS LISTED

	EBT/NBT	S/T/H[(a)]	RFP	CT[(b)]
PLASMA ENGINEERING SYSTEMS				
• Current Drive	NR	NR	0	NR
• Auxiliary heating				
- Startup	+	0	+	-
- Burn sustenance/control	+	0	0	-
• Equilibrium/stability/position control	-	-	0	-
• Plasma ash and impurity control	++	-	0	--
• Direct energy conversion	NR	NR	NR	-/UNK
• Fueling	0	0	0	-
NUCLEAR SYSTEMS				
• Limiters	0	+	0	NR
• Diverter plates	0	+	0	NR
• First wall(s)	0	+	+	+
• Blanket/shield	+	0	0	0
• Vacuum system	+	0	0	0
• Fuel handling/containment	0	0	0	0
MAGNET SYSTEMS				
• Toroidal-field coils	++	++	--	-
• Ohmic-heating coils	NR	NR	0	NR
• Equilibrium-field coils	NR	+	0	NR
• Divertor coils	++	-	+	NR
• Feedback/position-control coils	UNK	0	0	NR
• Power/energy transfer and storage	NR	NR	-	-
REMOTE MAINTENANCE SYSTEMS				
• Scheduled	-	+	-	-
• Unscheduled	-	+	-	-
DIAGNOSTICS AND I/C SYSTEMS	0	0	0	-
SAFETY AND ENVIRONMENTAL SYSTEMS	0	0	0	0

(a)Ranking based primarily on modular version of the stellarator[15,17] A study and inter-comparison between modular versus continuous coil S/T/H systems is in progress.[14]

(b)Ranking based on most "conventional" of the CT reactors listed on Table VII, the translating plasmoid CTOR.[60-62]

+ more difficult that tokamak
- less difficult than tokamak
0 similar to tokamak
NR not required
UNK unknown requirement

for the EBT/NBT, RFP, S/T/H, and CT. The potentially large startup power, thermally-unstable and collisionality-sensitive burn, and ambipolar effects on both transport and impurity/ash accumulations contribute, on the basis of present understanding, to the "more difficult" rating suggested for EBT/NBT. In addition, the factor by which the average plasma beta must be increased in order to achieve a viable reactor is considerably larger for the EBT/NBT. The impact of the relativistic electron rings needed for stability/equilibrium on the overall energy balance and beta issues, based on present knowledge, also contributes to this EBT/NBT ranking relative to the tokamak in this area. A potentially lossy, turbulent startup for RFPs may present a unique problem if the RFP minimum-energy state must be accessed during startup through an initial tokamak-like state, although other plasma engineering processes are expected to be similar to those for tokamaks. Furthermore, the RFP has already achieved reactor-like betas, although, like the tokamak, the RFP must address the issues of long-pulsed operation <u>versus</u> steady-state current drive. It is also noted that unlike the other AFCs being considered here, only the RFP promises ignition through by Ohmic heating alone. The startup and burn sustenance on externally-controlled flux surfaces (at least at low beta) appears as an advantage for S/T/Hs, although, like the tokamak, the stellarator presently operates at beta values that are 6-8 times below values needed for an economic reactor. The combination of exo-reactor plasmoid formation and ignition followed by a relatively passive burn for the translating versions of the CT reactors may contribute to significantly reduced engineering needs in this area; it must be recognized, however, that CTs are the least mature of all AFCs considered here.

2. <u>Nuclear Systems</u> Although the engineering needs for the Nuclear Systems are generally comparable for the mainline tokamak and the conventional AFCs, to varying degrees each AFC may present added engineering demands in this area. The desire or need to minimize the distance between the (superconducting) coil and plasma for EBT/NBT in order to maximize the bounce-averaged ratio of toroidal to local magnetic-field curvature for the purposes of minimizing transport losses at acceptable levels of aspect-ratio enhancement places added constraints on the blanket/shield design for EBT/NBT. The three-dimensional, helical character of the S/T/H presents added difficulty for engineering systems (FW/B/S, magnetic divertors) that must also adapt to this helical symmetry while, like the EBT/NBT, requiring thin FW/B/S systems immediately under the

superconducting (modular) coils. The possible role of the first wall as a flux-conserving, stabilizing shell may present unique needs for the RFP reactor, whereas the first-wall radiation flux may be significant at the entrance region of a linear burn chamber proposed for the translating-plasmoid CT reactor. Generally, the future engineering needs for the Nuclear Systems are expected to be comparable or somewhat more demanding than for the mainline tokamak. It is noted, however, that in certain areas, those needs for the tokamak remain to be fully resolved, the electrical role of the tokamak B/S, the optimal inboard B/S configuration, and the FW/B/S response to plasma current disruptions representing several example.

3. Magnet Systems When compared in terms of peak conductor fields, forces, and support/conductor mass and complexity, the magnet systems for both EBR/NBT and S/T/H present more difficult engineering systems than those expected for the tokamak. The tokamak topology problem related to interlocking poloidal and toroidal coils does not exist for the EBT/NBT, however, and can be considerably reduced or eliminated for the S/T/H. Since both EBT/NBT and S/T/H plasmas ideally do not support currents that could adjust or "heal" local field inhomogenities, coil alignment and field errors must be held to close tolerances. The low-field magnet systems for the conventional RFP appear from an engineering viewpoint to be considerably easier than for the tokamak, although the applicability of magnetic divertors in an RFP geometry has yet to be demonstrated. The long-pulsed conventional RFPR requires that both superconducting toroidal and poloidal coils operate in a ~ 5-10 T/s pulsed mode. The magnet system for a passive, translating-plasmoid CT reactor should present a considerably simplified (solenoidal) system than that for the tokamak, given the possibility for exo-blanket shell stabilization of a plasmoid that would slowly drift along a relatively low-intensity solenoidal guide field. The requirements imposed on any magnet system by the plasma physics for a given desirable engineering performance through the maximum allowable beta for a given power density or first-wall neutron loading is strongly dependent on the confinement system, with the tokamak and S/T/H demanding more of the magnets in order to compensate for lower plasma betas. The CTs and RFPs in this context require less of the magnet system, particularly for the RFP with plasma confinement provided primarily by poloidal field. The potentially high-beta EBT/NBT may also have a difficult coil problem if conventional aspect-ratio-

enhancement methods prove necessary; this problem becomes acute for EBT/NBT if beta limits are imposed that are considerably below those assumed by all past reactor studies, particularly when the complex interaction between beta, peak field at magnets, electron-ring energy losses, stability/equilibrium requirements, fusion yield (i.e., wall loading and system power density), recirculating power, and total system size and cost are self-consistently taken into account.

4. Remote Maintenance Systems The conventional AFCs listed on Table II are all moderate (RFP, S/T/H) to high (EBT/NBT, CT) aspect ratio devices, with the CT being considered here as linear. Although the S/T/Hs are moderate aspect ratio devices compared to the low aspect-ratio tokamak, the modular-coil S/T/H reactor studies[15,17] to date have yet to identify a full maintenance scheme that does not require the movement of massive coils ($\gtrsim$ 500 tonne). In fact, if the modular-coil versions of the S/T/Hs lead to coil systems that are too massive for remote movement, serious reconsideration must be given to versions based on the continuous-helix coil[16]; the better physics (magnetics) performance allowed by the latter presents an added incentive for continuous-coil S/T/H systems. Because of an efficient use of (poloidal) magnetic field, the conventional RFP reactor can be designed with a relatively open coil set that trades off increased stored (poloidal-field) energy and lower coil-to-plasma inductive coupling with a more open and accessible coil set. The high-aspect-ratio EBT/NBT, like the translating-plasmoid CT, provides ready access for maintainence, although EBT/NBT reactors based on conventional aspect-ratio-enhancement coils appear to be somewhat encumbered by a relatively massive and expensive coil set. Generally, modular-coil versions of the S/T/Hs appear to be more difficult to maintain then the tokamak, whereas the engineering needs with respect to maintenance access for the EBT/NBT, RFP, and CTs appear to be increasingly relaxed relative to the tokamak.

5. Other Systems Recognizing that the last two systems listed on Table VII generally receive marginal attention, little difference is expected between the tokamak and the conventional AFCs in diagnostics and I/C requirements. The passive, translating-plasmoid CTs may require less diagnostic and I/C development, at least in the burn chamber. Safety/environmental advantages may be attributed to the RFP and to CTs, in that both approaches are

expected to store considerably less magnetic-field energy than the tokamak, the S/T/H, or the EBT/NBT. All systems are expected to require similar tritium inventories per unit power for a similar blanket structure. A similar comment can be made with respect to the rate of (structural) radwaste generation per unit power output; blanket material will also be consumed at comparable rates when expressed on a tonne/MWt/y basis (~ 200–300 tonne/y for a ~ 4000-MWt plant).

5. Summary for Conventional AFCs Notwithstanding the abovementioned differences and with the possible exception of the less mature CT concepts, the conventional AFCs considered here appear similar (or somewhat more demanding in the case of EBT/NBT and S/T/H) in their future engineering needs for a number of key fusion-power-core systems. It is expected that a long-pulsed conventional RFP may present an equivalent, if not somewhat easier and more rapid, engineering path to fusion power than an equivalently long-pulsed tokamak,[30] if both systems operate with nominally the same plasma transport at fusion conditions. Although being vigorously addressed for the tokamak, the concept of steady-state current drive for the RFP remains to be developed.[29] Lastly, the relatively positive position for the (translating) CT reactor reflected in Table VII must be viewed in conjunction with the relative immaturity for these newer, but promising, approaches.

B. Technology R&D Needs for Compact (HPD) AFCs

The R&D needs perceived for HPD fusion options have not been quantified to the level that exists for the conventional mainline or AFC approaches. The technology R&D requirements for the HPD AFCs are also summarized here on a subsystem basis given in Table VII. Generally, similar requirements exist for the HPD approach as found for all conventional approaches. A shift in emphasis, however, results from the following changes related directly to achieving HPD operation.

- Increased plasma power density, which is proportional to $\beta^2 B^4$, where B is the confining magnetic field at the plasma and β is the ratio of average plasma pressure to magnetic field pressure at the plasma surface.
- Increased first-wall neutron current ($I_w \simeq$ 15–20 MW/m^2) and surface heat flux ($I_Q \simeq$ 4–5 MWt/m^2) for operation without a divertor.

- Increased peak ($\gtrsim$ 100 MWt/m^3) and average (~ 50 MWt/m^3) power density within a tritium-breeding blanket.
- Increased radiation and heat fluxes at resistive magnet coils in systems designed to operate only with a thin HPD blanket placed between the coil and the plasma.

In relating these general features through the listing given in Table VII to identify specific and/or unique technology D&T needs, generic differences between confinement schemes being proposed for HPD applications must be taken into account. No systematic attempt is made here to identify device-specific issues. None of the potential HPD systems depicted on Table II (i.e., CRFPR, OHTE, Riggatron, as well as a range of CTs[62] and high-beta stellarators[77]) have been examined as a reactor at the level even approaching that of the mainline tokamak and TMR or certain of the conventional AFCs (i.e., EBT/NBT, RFP, a number of the CTs). Nevertheless, the following general technology R&D needs can be identified for the HPD options.

1. Plasma Engineering Systems The higher plasma density envisaged for the compact systems will impact all items listed on Table VII under this system. All three HPD approaches summarized on Table IV rely on significant Ohmic heating by toroidal plasma currents. The high-field tokamak in addition may require auxiliary (adiabatic compressional and/or rf) heating to achieve ignition. The high plasma density makes rf current drive more difficult, although low-frequency F-Θ pumping of currents in RFP-like plasmas[89] should not be strongly effected by the higher plasma density. Plasma-ash, impurity, and fueling control remains as uncertainties in the higher density regime; dense gas blanket and/or magnetic divertors are being considered and will undoubtedly be required even for long-pulsed operation, particularly if first-wall protection against sputtering proves necessary. The first-wall response to the plasma/wall interaction, rather than high-heat transfer rates *per se*,[90] represents the key plasma-engineering issue for the HPD option.

2. Nuclear Systems The increased surface heat flux and volumetric power density at the first-wall and within the tritium-breeding blanket represent a major impact on the technology D&T goals/requirements for the Nuclear Systems. Preliminary computations[90] find no serious thermomechanical problem under long-pulsed operation for a CRFPR using a high-strength copper alloy at the first-wall that is cooled by high-pressure water ($\lesssim 10^6$ pulses, I_w = 15-20 MW/m^2,

$\gtrsim$ 30-s burn, one-year operating life). Use of primary candidate alloy stainless steel (PCASS) would be out of the question, however, in this application. It is noted that these heat fluxes are required of the STARFIRE pumped limiter,[3] which itself has an area that is ~ 50% times that of the entire CRFPR first wall. Although first-wall heat transfer in either case appears to present no serious engineering problems, as noted above, the questions of sputtering and non-uniform energy deposition present serious uncertainties for all HPD approaches; this central issue is closely related to the projected engineering/technology needs for both the plasma engineering systems (i.e., dense gas blankets, refueling, divertors, etc.) and the magnet systems (divertors). The peak blanket power density ($\gtrsim$ 100 MWt/m^3) is comparable to the power density in a light-water reactor (LWR) fission core, and the compatibility of solid tritium breeders with this local power density presents a question. The LiPb-cooled blanket proposed for the OHTE[34,35] appears particularly attractive for these HPD applications, especially for the relatively low-field RFP geometry, where MHD-pumping losses can be considerably reduced. A fully-optimized design of such a thin, tritium-breeding, energy-efficient blanket, however, remains to be made. Generally, the impact on the technology R&D required of the Nuclear Systems will uniformly be the greatest for the HPD approaches, although for certain HPD confinement schemes[35,36] the impact on the magnet systems will be equally as great.

3. Magnet Systems The magnet requirements for the three HPD approaches listed on Table IV differ widely. For those systems requiring large toroidal (tokamak) or helical (OHTE, perhaps high-beta stellarators) fields, resistive coils positioned at or near the first wall may be required because of force or inductive- and/or plasma-coupling considerations. In these cases, the reactor energy balance will be degraded. The dominance of plasma pressure confinement by poloidal field in the RFP, on the other hand, allows the use of exo-blanket coils operating with low fields, small amounts of stored energy, and Ohmic losses that can be made a small fraction of the total fusion power. For all cases, however, these resistive coils must operate in a relatively high radiation flux, requiring the use of inorganic electrical insulation and near-room-temperature copper (or aluminum) conductors. Although the toroidal-field coils dominate the HPD tokamak Magnet System, the Ohmic-heating/poloidal/equilibrium coils dominate the HPD RFP design, and the first-

wall helical coils dominate the OHTE reactor, the questions of divertor coils and feedback/position-control coils remains to be fully answered for all HPD concepts. For those HPD systems that propose a long-pulsed operation, the method adopted for power/energy transfer and storage (PETS) can present a key cost issue and is intimately associated with key physics issues related to plasma startup and approach to ignition. Ideally, transfer times and total energy requirements that are most suitable for direct drive from the electrical grid would be preferable. Generally, the greatest demand on magnet and PETS systems occurs during plasma startup, a demand that is strongly determined by poorly understood, fundamental plasma processes occurring during the startup transient. The amount of flux-drive required for long-pulsed operation or current-drive power required for steady-state operation is also closely related to the degree to which the electrical resistivity of the burning plasma is anomalous; anomaly factors in excess of 10 can seriously degrade the overall plant performance in terms of PETS cost and added recirculating power requirements.

4. Remote Maintenance Systems A major goal of the HPD approaches is to achieve fusion-power-core mass utilizations in the range 0.5-1.0 tonne/MWt. At the lower limit a 4000-MWt (~ 1000-MWe) power plant would be driven by a fusion power core (FW/B/S/C) that weighs less than 1500 tonne. This mass is equivalent to at most a few of the many toroidal-field coils envisaged for some of the more conventional approaches given in Table I. It is therefore conceivable that the entire fusion power core could be replaced as a single or at most a few units during an annually scheduled maintenance period. Typically, the complete FW/B/S system for this ~ 1000-MWe power plant would weigh 200-300 tonne, and at the 15-20 MW/m^2 first-wall loading would be subject to annual replacement. This annual replacement rate, of course, is comparable to that for the conventional fusion systems (FW/B/S weighs 8300 and 17,401 tonnes, respectively for STARFIRE[3] and EBTR[23]), which would replace only a fraction of the FW/B/S each year. Both conventional and HPD approaches to MFE would "burn" FW/B systems at comparable rates (200-300 tonne/y for a ~ 4000-MWt plant) and therefore would be subjected to similar operating and associated (incremental) COE costs. The investment cost for the fusion power core, however, would be considerably less for the HPD approaches. Equally if not more important, a more rapid and reliable FW/B/S replacement scheme based on total (block) maintenance approaches could lead to

enhanced overall plant availability which in turn can counteract potentially lower operational reliability and more frequent changeouts associated with these higher-performance systems. In any event, the concept of block maintenance, wherein the entire fusion power core or at least the FW/B/S is replaced as a single unit, offers a completely new and innovative maintenance approach for both scheduled and unscheduled outages.

5. Other Systems Technology R&D needs for the HPD reactor in the diagnostics [illegible] systems area are poorly understood even for the conventional approaches [illegible]E. Little can be said about similar needs for the HPD approaches beyond the discussion given in Sec. III.A.5. In terms of total rate of radionuclide generation, little difference is expected between conventional and HPD approaches. For a given tritium solubility in a Li-Pb blanket, the HPD systems are expected to operate with reduced inventories of "vulnerable" tritium. Although the HPD device will store considerably less magnetic energy in a room-temperature rather than a cryogenic magnet set, the density of radionuclide generation and the related nuclear afterheat problem will scale with the increased system power density. Given that each tonne of FW/B will generate similar amounts of total energy for both approaches, the structural radwaste problem is expected to be similar for both conventional and HPD approaches.

6. Pulsed versus Steady-State Operation Like the mainline tokamak, most systems being considered for HPD operation intrinsically would operate in a long-pulsed mode. It is emphasized that the thermal power delivered to the turbine and the electrical energy generated by the turbine/generator systems would always be steady state; only the plasma and to some extent the first wall is cycled in the long-pulsed system. A high-beta S/T/H (e.g., Heliac), however, would be intrinsically steady state, although crucial and interrelated geometric, stability/equilibrium, and beta issues remain to be resolved. A high-duty-cycle, long-pulsed operating mode for RFPs, OHTEs, CTs, and HPD tokamaks can be made to resemble closely a truly steady-state operation, particularly if the startup/rundown schedules are engineered to minimize thermal transients both at the first wall and within the blanket. Like the tokamak,[3] steady-state current drive for both RFPs and OHTEs can be proposed.[89] Steady-state DT plasma densities in the ~ $3\text{-}10(10)^{20}\ m^{-3}$ range and plasma minor radii

in the range 0.5–0.7 m are projected; this higher density will impact the engineering/technology D&T requirements for the first three systems listed in Table VII.

Generally, the attraction of "steady-state operation" has been so intense as to obsure the added engineering/technology/physics D&T needed to achieve this goal. In addition to new and often difficult requirements for steady-state current drive for those devices requiring toroidal currents beyond ~ 100 s, the issue of active refueling and impurity/ash control contributes to the uncertainty of that approach. Embracing truly steady-state confinement schemes (EBT/NBT, S/T/H, TMR) brings equally serious uncertainties of beta/stability/equilibrium (EBT/NBT, S/T/H), applicability or compatability of the magnetic divertor (EBT), and overall system efficiency (EBT/NBTs electron-ring losses, TMRs end losses). Superposed onto these uncertainties is the tendency of any closed-field steady-state plasma to establish radial electric fields that may enhance the trapping of helium ash, thereby necessitating periodic (~ 30 s) plasma shutdown for ash purge. Lastly, efficient plasma operation in relatively small HPD systems may bring advantages that subjugates the issue of long-pulsed <u>versus</u> steady-state reactor operation; this tradeoff must be understood more clearly before establishing a priority for the many future engineering needs of MFE, only one of which being a desire for steady-state plasma operation.

IV. SUMMARY AND CONCLUSIONS

The discussion given in Sec. III has been qualitative and wide ranging. This qualitative assessment of the future engineering/technology needs of the AFCs is summarized in tabular form below. No inference should be made about the relative number of items/issues listed per reactor system for any given AFC.

TABLE VIII

FUTURE ENGINEERING/TECHNOLOGY NEEDS OF AFCs

PLASMA ENGINEERING SYSTEMS

CONCF	NEEDS
EBT/NBT	• Resolve crucial interdependency of electron-ring size (i.e., thickness), collisional drag loss (i.e., recirculating power), plasma density profiles, and maximum core-plasma beta. • Startup scenario that controls density, electron heating, and ion heating to minimize startup power and to achieve a stable ignition. - maintain electron collisionality in a narrow range (i.e., operate in the T mode). - electron/ion heating to keep $T_e \approx T_i$ and to assure radial electric fields are maintained. - startup trajectory that satisfies above, minimizes power, and achieves stable ignition. • Develop acceptable magnetic divertor compatible with local field curvature required by transport. • Better understand role of edge-plasma boundary on bulk-plasma behavior, control of ambipolar potential. • Better reactors emerge for positive electric fields and more collisional plasmas; need exists to reconcile relevant physics with this reactor regime.
S/T/H	• Better resolve/understand the effects of magnetics on beta/transport/stability/equilibrium and crucial interdependence on FW/B/S/C engineering design and system economics. • Minimum-power startup scenario that properly adjusts flux surfaces as beta increases to ignition. • Maximize plasma filling fraction for non-circular shapes (toroidal ripple, limiter *versus* divertor). • Understand role of ambipolor electric fields on transport and stability/equilibrium.

RFP

- Startup scenario that minimizes power and volt-seconds as minimum-energy RFP state and ignition is achieved.
- Steady-state current drive by low-frequency, F-Θ pumping with minimum reactive power.
- Develop a divertor (single null, inboard, poloidal) that is compatible with RFP magnetics.
- Understand/develop toroidal-field ripple constraint for RFPs.
- Impact/need of conducting FW shell.

CT

- Scale to and develop means for exo-reactor plasmoid formation (co-axial gun, FROP, hard core), plasmoid heating (compression, rf, NBI), and translation to burn chamber.
- Better understand the relationship between transport, profiles, and stable life of plasmoid.
- Develop means for steady-state current drive/refluxing of a stationary, ignited plasmoid.
- Means to refuel a translating plasmoid and recover energy directly from spent plasmoid.

HPD OPTIONS

- Operate with high current density ($\gtrsim 10\ MA/m^2$) in a dense plasma to achieve DT ignition by Ohmic heating alone, possibly with auxiliary-heating boost or preconditioning.
- Understand means to provide fueling, impurity/ash control, and steady-state current drive in dense plasma.
- Plasma-edge control, dense gas-blanket, isolation of plasma from FW scrape-off layer required.
- Examine potential of HPD options for confinement systems that operate with currentless plasma.

NUCLEAR SYSTEMS

CONCEPT	NEEDS
EBT/NBT	• Two-region, azimuthally non-symmetric B/S is needed to minimize distance between TF/ARE field-shaping coils and plasma, while maintaining adequate tritium breeding and shielding of SC. • High-power rf protection of FW/B/S subsystems, vacuum ducts, etc., and rf component lifetime in radiation environment (windows).

S/T/H	• Stability/equilibrium/beta-dictated magnetics may require thin, sub-breeding B/S directly under coils, like EBTs.
	• Engineer, support, install, maintain helically arrayed FW/B/S, divertor and coil systems.
RFP	• Possible need of an electrically conducting first wall, impacts overall plant efficiency, assembly/maintenance scheme (gaps), and FW/B lifetime.
CT	• Means to deal with high heat flux at entrance of linear burn chamber for systems based on exo-reactor formed/ignited, translating-plasmoid systems.
	• *In situ* high-voltage FW/B for stationary, shock-heated, adiabatically compressed plasmoids (TRACT).
	• Thermal/hydraulic/neutronic/mechanical aspects of liquid-metal liner-compressed approaches (LINUS).
	• NBI penetrations and potential need for quadrupole windings in the FW/B region (FRM).
	• Engineering needs of CTs formed from plasma gun or hard core and subsequently burned in a steady-state, stationary mode are poorly understood (little study).
FPD OPTIONS	• High heat-flux (3-5 MW/m^2) FW and high-power-density breeding blanket (200 MWt/m^3 peak, 50-100 MWt/m^3 average) precludes use of PCASS and solid breeders.
	• Control/understand FW sputter erosion through divertor or dense gas blankets.
	• Single/few-piece FW/B/S construction for purposes of "block" maintenance requires careful resolution.

MAGNET SYSTE

CONCEPT	NEEDS
EBT/NBT	• Better methods needed to achieve ARE than the "conventional" means, which gives a massive, inefficient coil set with a coil-to-on-axis field ratio of ~ 3 (βB^2 still low, even with high beta).
	• Design and feasibility of a magnetic divertor in a steady-state bumpy torus (ambipolar fields, bounce-averaged field curvature for good transport).

- Field errors associated with coil construction and torus assembly must be held to low values because of inability of a currentless plasma to "heal" field inhomogenities and fluctuating/unconfined flux lines. Need for truly currentless plasma operation.

- Effect of field fluctuations associated with high-power ICRH/LHH startup on line closure and confinement must be better understood.

- Better understanding/design of loss-of-coil accident and methods to recover.

S/T/H

- Need for accurate coil alignment, as for EBT/NBT and for similar reasons.

- Effect of field fluctuations associated with high-powered LCRH/LHH startup on magnetic island formation, vertical field and confinement.

- The proximity of opposing current conductors and the associated forces not as serious as for EBT/NBT, but the problem nontheless exists for S/T/H. Need arise for methods to achieve desired magnetics with less massive (costly) coil sets.

- Adjust/tune magnetics as plasma beta is increased during startup to maintain stability/equilibrium condition.

- Need better engineering understanding of β versus on-axis B tradeoff between EBT/NBT and S/T/H. For same βB^2 (plasma power density) S/T/H has higher B for a given limit imposed on the coil field, and a lower β is possible, compared to EBT/NBT.

- Non-planar coil fabrication and winding required, cannot wind modular coils under tension, unlike yin-yang coils for TMR.

RFP

- Long-pulsed SC option requires 5-10 T/s PFCs and TFCs, but operation is at low fields (2-3 T). Only SC AFC reactor that can solely use NbTi technology.

- Steady-state SC operation may require poloidal divertors, charecteristics of which are unknown for RFF geometry.

- Position-control, stability/equilibrium feedback coils required, but remains uncharacterized.

CT

- Magnet requirements vary widely for various CT reactor approaches (simple solenoid, quadrupoles, hard cores, no magnets), but high-beta plasmoids generally leads to reduced magnet requirements.

- CT reactor extrema insofar as magnet needs are concerned
  - TRACT: high-field hydrid magnets positioned around an ignited plasmoid.
  - LINUS: no in-reactor magnet requirement.

HPD OPTIONS

- Very high-field (20-25 T) first-wall resistive coils required by Ohmically-heated HPD tokamaks.
- Most HPD systems (CRFPR, Riggatron, OHTE, Heliac) require resistive coils to operate in high radiation field. Need exists to understand response of such coils and life-limiting mechanisms.
- Certain HPD options successfully tradeoff higher recirculating power and BOP cost for reduced shield and coil costs; this tradeoff requires additional study.
- Generally, exo-blanket coil design/requirements are state-of-the-art.

REMOTE MAINTENANCE SYSTEMS

CONCEPT	NEEDS

EBT/NBT

- Maintenance of the high-aspect-ratio design based on conventional ARE requires movement of 69.9 tonne midplane FW/B/S module and a 44.4 tonne coil-plane FW/B/S module through a fixed coil set. Maintenance advantages would be retained at R_T/r_p values considerably below the ~ 35 used with conventional ARE. Enhanced maintenance would result from simpler, more open means to achieve ARE, even at lower aspect ratios.
- Eliminate auxiliary coils for ARE, and achieve high R_T/R_C solely through deformed, canted, and/or lower aspect-ratio TFC set.
- Each of 36 TF/ARE-coil units weights 726 tonne, which has led to a life-of-plant coil design. This assumption must be re-examined.

S/T/H

- Maintenance scheme similar to EBT/NBT, wherein the more complex S/T/H coils (400-500 tonne each) remain fixed, but system is lower aspect ratio and perhaps more open and amenable for FW/B/S module extraction.
- Impact on maintenance scheme of realistically designed coil-support and bucking-ring systems, as well as divertor/vacuum system, must be better resolved.
- Maintenance problems on a modular but helically arrayed system of FW/B/S segments needs better resolution.

- The key issue of fixed modular coils versus fixed continuous-helical coils with respect to maintenance of a segmented/modular FW/B/S must be better resolved.

RFP

- Ability to locate PFC set outside the fusion power core, at an added but acceptable cost in stored field energy, gives a relatively open torus comprised of FW/B/S and low-field TFCs. The TFC could remain fixed, or be moved with a given FW/B/S module.
- FW/B/S maintenance scheme calls for partial in situ disassembly (i.e., separate blanket and shield), leading to less mass per lift. Feasibility of this operation should be better resolved.
- Conducting-shell FW and allowable gap spacing impact strongly FW/B module size and attachment scheme. This important issue must be better understood.

CT

- Wide range of configurations are possible:
  - translating plasmoid moves high-technology systems outside reactor and into a reduced radiation environment.
  - stationary CT reactors (LINUS, TRACT) also differ widely, with TRACT depending on the survival of the high-technology FW/B/S/C and the LINUS each pulse regenerating a liquid-metal FW/B/S/C.

HPD OPTION

- The basic maintenance approach differs considerably from the conventional mainline and AFC concepts; total "block" maintenance of the FW/B/S ($\sim$ 200-300 tonne) is proposed. The merits of "block" versus "patch" maintenance requires further examination.

On the basis of this qualitative assessment no suprises arise with respect to the key areas of engineering need for the AFCs relative to the better defined needs of the mainline concepts. Specifically, the future engineering need of both mainline and AFC MFE approaches lie primarily in the following areas.

- Plasma Engineering (auxiliary and/or startup heating, impurity/ash/fuel control, current drive versus pulsed operation).
- First-wall/Limiter (transient thermal effects, sputtering, radiation effects, tritium permeation/retention/recycle, end-of-life mechanism(s) and lifetime).

- Blanket/Shield (materials compatibility, radiation damage, solid-breeder properties versus liquid-metal breeder containment).
- Magnets (thermomechanical/electromechanical properties, radiation effects, reliability, maximum fields and hybrid magnets, size/modularity).
- Remote Maintenance (better definition of maintenance scheme, need for less massive modules).

The difficulty of the problem(s) associated with any of these key engineering areas depends crucially on the confinement physics. Each AFC listed on Table I to varying degrees has the potential for improved (reduced) engineering needs relative to the mainline concepts by offering differences in some aspect of confinement physics. Generally, improvements perceived for one area have been or can be expected to be accompanied by the creation of new unknowns or the worsening of conditions in other areas. Over the past decade, iteration over this improvement/disimprovement cycle has narrowed the AFCs to S/T/H, EBT/NBT, and RFP, with the more recent interest in CTs arising because of the unique potential of decoupling totally the coil set from a high-beta plasma. It should be noted that this process has occurred largely without direct comparisons or intercomparisons with the evolving tokamak or mirror concepts.

Relative to the mainline tokamak and TMR concepts, each of these AFCs offer technological improvements that in turn are projected on the basis of certain extrapolation of physics performance. These extrapolations vary widely. Any relative ranking of the mainline and AFC approaches based on engineering/technology needs will be obscured by uncertainties in the physics data base, the level of concept maturity, and required extrapolations. Generally, the future engineering needs of the conventional AFCs are anticipated to be largely satisfied by programs required by the mainline tokamak and mirror approaches; even the complex coil requirements of the S/T/Hs or the high-power/high-frequency rf requirements envisaged for EBT/NBTs could be met by satisfying similar if not more profound requirements of the tandem mirrors. The existence of this situation is not surprising, in that the conventional AFCs and the mainline approaches are projecting MFE reactors that appear to be quite similar when measured in terms of size, power density, basic engineering D&T needs, and level of technological and economic risk.

The ability of any MFE concept to project to the HPD regime will depend on the fulfillment of future engineering needs that may not automatically emerge from D&T programs put in place for the more conventional approaches.

Nevertheless, the conventional mainline approaches may supply important engineering information for the HPD options in the area of high heat-flux first-walls (pumped limiters for tokamaks, direct convertor surfaces for tandem mirrors) and radiation-resistent resistive coils (equilibrium coils for tokamaks, high-field hybrid magnets for the tandem mirror end cells), as well as pulsed power/energy transfer and storage (tokamak startup). All these areas are considered to represent long-term development items for the mainline approaches, however, whereas many of the related engineering problems must be addressed by HPD experiments on a much shorter time scale. Unlike the conventional AFCs, the compact HPD option must be considered as a true option rather than as a backup to the mainline approaches, in that both the time schedule for and re-emphasized needs of the HPD option will not allow key engineering issues to be resolved by the D&T programs in place for the mainline tokamak or mirror systems. If a single future engineering need can be identified from this survey it would call for a careful and concerted effort to understand the degree to which existing technologies can be extended to accommodate the needs of the HPD option compared to the elimination or deduction of other technologies that lie far beyond direct extentions of or extrapolations from that which is known.

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